TOPICAL MEETING ON ULTRASOUND CHARACTERIZATION OF CANCELLOUS AND CORTICAL BONE

(AT THE 148TH MEETING OF THE ACOUSTICAL SOCIETY OF AMERICA)

LOCATION: San Diego, California
DATE: Monday, 15 November 2004
ASA MEETING WEBSITE: http://asa.aip.org/meetings.html
TOPICAL MEETING WEBSITE: http://www.boulder.nist.gov/div853/bone.htm

CO-CHAIRS: Kendall R. Waters (NIST)
Brent K. Hoffmeister (Rhodes College)

DESCRIPTION: A one-day colloquium and discussion on the topic "Ultrasound Characterization of Cancellous and Cortical Bone" will be held. Subtopics will focus on the following areas: Propagation and Scattering Models, Experimental Measurement Techniques, and Clinical Impact and Comparison with Other Characterization Modalities. Each subtopic session will consist of invited and contributed papers. A panel discussion will be held at the end of the day.

FULL AGENDA (WITH ABSTRACTS)
(AS OF OCT. 07, 2004)

(25 min for Invited Papers, 15 min for Contributed Papers)

Topical Meeting on Ultrasound Characterization of Cancellous and Cortical Bone I: Propagation and Scattering Properties

7:55 am: Welcome and Introductions

8:00 am: 1aBB1 **(INVITED)**

Author(s): Keith A. Wear.

Affiliation: FDA CDRH HFZ-142, 12720 Twinbrook Pky., Rockville, MD 20852

Title: Ultrasonic wave propagation and scattering in cancellous bone

Abstract: Theoretical models and experimental data describing the interaction between ultrasound and cancellous bone will be discussed. Ultrasonic attenuation in cancellous bone is much greater than that for soft tissues and varies approximately linearly with frequency between 400 kHz and 1.7 MHz. Speed of sound in cancellous bone is slightly higher than that for soft tissues and decreases gradually with frequency at diagnostic frequencies (between 300 and 700 kHz). The dependence of phase velocity on porosity may be predicted from theory of acoustic propagation in fluid-filled porous solids. The negative dispersion can be explained using a stratified two-component model. At diagnostic frequencies, scattering varies approximately as frequency to the nth power where $3<n<3.5$. This may be explained either by a continuous or discrete scattering model. The latter represents trabeculae as small finite-length cylindrical scatterers. The frequency dependence of scattering, along with the anisotropy of scattering and attenuation, implies that absorption is a greater source of attenuation than scattering. [Funding from the FDA Office of Women's Health is gratefully acknowledged.]

8:25 am: 1aBB2 **(INVITED)**

Author(s): Zine El Abiddine Fellah[1], Jean-Yves Chapelon[1], Walter Lauriks[2], Claude Depollier[3]

Affiliation: [1]INSERM, unite 556, 151 cours Albert Thomas, 69424 Lyon, France; [2]Laboratorium voor Akoestiek en Thermische Fysica, Katholieke, Belgium; [3]Laboratoire d'Acoustique de l'Universite du Maine, UMR-CNRS, France

Title: Ultrasonic wave propagation in human cancellous bone: Application of Biot theory

Abstract: Ultrasonic wave propagation in human cancellous bone is considered. Reflection and transmission coefficients are derived for a slab of cancellous bone having an elastic frame using Biot's theory modified by the Johnson et al. model for viscous exchange between fluid and structure. Numerical simulations of transmitted waves in the time domain are worked out by varying the modified Biot parameters. The sensitivity of each physical parameter used in the theory has been studied in transmission. Some parameters play an important role in slow wave waveform, such as the viscous characteristic length and pore fluid bulk modulus. However, other parameters play an important role in the fast wave waveform, such as solid density and shear modulus. We also note from these simulations that some parameters, such as porosity, tortuosity, thickness, solid bulk modulus and skeletal compressibility frame, play an important role simultaneously in both fast and slow waveforms compared to other parameters which act on the waveform of just one of the two waves. Experimental results for slow and fast waves transmitted through human cancellous bone samples are given and compared with theoretical predictions.

8:50 am: 1aBB3 **(INVITED)**

Author(s): Jonathan J. Kaufman[1], Gangming Luo[1], Robert S. Siffert[2]

Affiliation: [1]CyberLogic, Inc., 611 Broadway, Ste. 707, New York, NY 10012; [2]Mount Sinai School of Medicine, New York, NY 10012

Title: Simulation of ultrasound propagation in bone

Abstract: Ultrasound has been proposed as a means to noninvasively assess bone and, particularly, bone strength and fracture risk, as for example in osteoporosis. Because strength is a function of both mineral density and architecture, ultrasound has the potential to provide more accurate measurement of bone integrity than, for example, with x-ray absorptiometric methods. Although some of this potential has already been realized---a number of clinical devices are presently available---there is still much that is unknown regarding the interaction of ultrasound with bone. Because of the inherent complexity of the propagation medium, few analytic solutions exist with practical application. For this reason, ultrasound simulation techniques have been developed and applied to a number of different problems of interest in ultrasonic bone assessment. Both 2D and 3D simulation results will be presented, including the effects of architecture and density on the received waveform, propagation effects of both cortical and trabecular bone, and the relative contributions of scattering and absorption to attenuation in trabecular bone. The results of these simulation studies should lead to improved understanding and ultimately to more effective clinical devices for ultrasound bone assessment. [This work was supported by The Carroll and Milton Petrie Foundation and by SBIR Grant No. 1R43RR16750 from the National Center for Research Resources of the NIH.]

9:15 am: 1aBB4

Author(s): Brent K. Hoffmeister[1], Charles I. Jones III[1], Sue C. Kaste[2]

Affiliation: [1]Dept. of Phys., Rhodes College, 2000 North Pkwy., Memphis, TN 38112; [2]St. Jude Children's Res. Hospital, Memphis, TN 38105

Title: Apparent integrated backscatter from cancellous bone in the frequency range 2.5-7.5 MHz

Abstract: Ultrasonic backscatter may offer useful new techniques for ultrasonic bone assessment. For this study, backscatter measurements were performed on 18 specimens of bovine cancellous bone using a 5-MHz broadband ultrasonic system operating between 2.5--7.5 MHz. Specimens were obtained from the proximal tibia, and prepared in the shape of cubes (15-mm side length) with faces oriented along principal anatomic directions (anterior, posterior, medial, lateral, superior, and inferior). A mechanical scanning system was used to acquire ultrasonic backscatter signals from 144 sites perpendicular to each face of each cube. The signals were analyzed to extract values of apparent integrated backscatter (AIB), a parameter that represents the frequency-averaged backscattered power uncompensated for the effects of attenuation and diffraction. AIB demonstrated

highly significant linear correlations with bone mineral density (BMD) for both the transverse (anterior, posterior, medial, and lateral) and longitudinal (superior and inferior) directions. In all cases AIB decreased with increasing BMD. No significant anisotropy was detected. We conclude that AIB measurements performed on bovine cancellous bone in this range of frequencies correlate well with BMD.

9:30 am: 1aBB5

Author(s): Patrick H. Nicholson

Affiliation: Dept. of Health Sci., Univ. of Jyvaskyla, P.O. Box 35, 40014, Finland

Title: Some aspects of the atypical acoustic behavior of cancellous bone

Abstract: Cancellous bone, consisting of a porous framework of solid trabeculae saturated in marrow fluid, is a challenging material in terms of ultrasonic characterization. This study considers some unusual aspects of the ultrasonic behavior of cancellous bone. These anomalies highlight the boundaries of our knowledge and, arguably, point us towards promising directions for future progress. Profoundly different wave propagation regimes can exist along different anatomical axes. Along the main axis of trabecular orientation, two longitudinal waves are observed, but only one wave is observed for propagation transversely across the trabeculae. In the latter case, a positive attenuation slope and negative velocity dispersion are seen, in apparent violation of the Kramers--Kronig relations. The properties of the saturating fluid have major effects on acoustic properties, and temperature studies also point towards the importance of the fluid. In some clinical studies, velocity and attenuation in the heel show opposite changes, which is difficult to explain without considering the possibility of changes in the marrow as well as the bone. Shear wave propagation in fluid-filled cancellous bone has received little attention. Measurements in whale bone suggest that shear waves propagate in dry bone, but are rapidly attenuated in the presence of saturating fluid.

9:45 am: 1aBB6

Author(s): Kendall R. Waters[1], Brent K. Hoffmeister[2], S. A. Whitten[2]

Affiliation: [1]NIST, Mater. Reliability Div., 325 Broadway, Boulder, CO 80305; [2]Rhodes College, Memphis, TN 38112

Title: Dependence of dispersive properties of cancellous bone on bone mineral and collagen content

Abstract: Cancellous bone is known to exhibit dispersion over clinically-relevant ultrasonic frequencies. However, the dependence of the dispersive properties of cancellous bone on bone mineral and collagen content are currently not well understood. Cancellous bone specimens (n=16) obtained from the proximal end of bovine tibia were cut into cubes (15 mm sides) and prepared for measurement along the anterior-posterior (AP), medial-lateral (ML), and superior-inferior (SI) directions. Bone mineral densities (BMD) ranged from 100 to 250 kg/m[sup 3]. Subsets of the bone specimens were chemically treated to remove bone mineral (n[inf M]=10) and collagen content (n[inf C]=6). Ultrasonic measurements were performed before and after treatment in a water bath (23<th>(degrees)C) using a pair of 2.25-MHz planar transducers aligned coaxially. Phase

velocity was determined from Fourier analysis of the ultrasonic signals, and dispersion was calculated as the change in phase velocity across the usable bandwidth. Demineralization produced highly significant changes in dispersion along the AP ($p=0.004$) and ML ($p=0.002$) directions, but not the SI direction ($p=0.6$). Decollagenization produced no significant change for any direction ($p>0.3$). These results indicate that bone mineral plays a much larger role than collagen in the dispersive behavior of cancellous bone.

10:00 am: Break

10:15 am: 1aBB7

Author(s): Sabina Gheduzzi[1], Victor F. Humphrey[2], Simon P. Dodd[3], James L. Cunningham[3], Anthony W. Miles[3]

Affiliation: [1]Orthopaedic Surgery, Univ. of Bristol, AOC Lower Level, Southmead Hospital, Bristol BS10 5NB, UK; [2]Univ. of Southampton, UK; [3]Univ. of Bath, UK

Title: Ultrasound attenuation as a quantitative measure of fracture healing

Abstract: The monitoring of fracture healing still relies upon the judgment of callus formation and on the manual assessment of the stiffness of the fracture. A diagnostic tool capable of quantitatively measuring healing progression of a fracture would allow the fine-tuning of the treatment regime. Ultrasound attenuation measurements were adopted as a possible method of assessing the healing process in human long bones. The method involves exciting ultrasonic waves at 200 kHz in the bone and measuring the reradiation along the bone and across the fracture zone. Seven cadaveric femora were tested in vitro in intact form and after creating a transverse fracture by sawing through the cortex. The effects of five different fracture types were investigated. A partial fracture, corresponding to a 50% cut through the cortex, a closed fracture, and fractures of widths varying between 1, 2, and 4 mm were investigated. The introduction of a fracture was found to produce a dramatic effect on the amplitude of the signal. Ultrasound attenuation was found to be sensitive to the presence of a fracture, even when the fracture was well reduced. It would therefore appear feasible to adopt attenuation across a fracture as a quantitative measurement of fracture healing.

10:30 am: 1aBB8

Author(s): Iyad Al Haffar[1], Frederic Padilla[1], Pascal Laugier[1], Raphael Nefussi[2], Sami Kolta[3], Jean-Michel Foucart[4]

Affiliation: [1]Laboratoire d'Imagerie Parametrique, CNRS UMR 7623, Universite Paris 6, 15 rue de l'Ecole de Medecine, 75006 Paris, France; [2]Laboratoire de Biologie, 75006 Paris, France; [3]Universite Rene Descartes, Paris, France ; [4]Service d'Imagerie Medicale Hotel-Dieu de Paris

Title: Experimental evaluation of bone quality using speed of sound measurement in cadaver mandibles

Abstract: This study is the first attempt to use speed of sound (SOS) as a new ultrasonic diagnostic tool for bone quality assessment before oral implant treatment. The objective is to demonstrate the in vitro feasibility of local SOS measurement at the mandible, and to investigate the relationships between mandibular SOS and local bone mineral density (BMD) and the ratio between the trabecular and cortical thickness (Tb.Th/Cort.Th). Fourteen excised human mandible were measured in transmission with a pair of flat 1.6-MHz central frequency transducers. Three regions of interest (ROIs) were selected in the specimens: incisor, premolar and molar regions. Ten measurements with repositioning were performed on each ROI to determine the short-term precision. Dual x-ray absorptiometry scans were performed on the samples for local BMD measurements. Computed tomography (CT) was used to determine mandibular cross-sectional morphological measurements. SOS measurements at different sites were significantly different, reflecting the heterogeneity between the different sites. A strong linear relationship was found between SOS and BMD (r^2=0.68, p<0,0001) while a nonlinear relationship was found between SOS and Tb.Th/Cort.Th (r^2=0.48, p<0,0001). This study demonstrates in vitro the feasibility of SOS measurement at the mandible. In vitro mandibular SOS reflects local BMD and Tb.Th/Cort.Th before implant.

10:45 am: 1aBB9

Author(s): Frederic Jenson, Frederic Padilla, Pascal Laugier

Affiliation: Laboratoire d'Imagerie Parametrique, CNRS UMR 7623 Universite Paris 6, 15 rue de l'Ecole de Medecine, 75006 Paris, France

Title: Investigation of ultrasonic properties of human hip bone: relationship to bone mineral density (BMD) and micro-architecture

Abstract: The goal of this study is to investigate the relationships between QUS measurements (transmission and reflection) and BMD and micro-architecture measured on human proximal femur. Thirty-eight 1-cm thick slices of trabecular bones were removed from fresh human proximal femurs. Two-dimensional scans were performed using 1-MHz focused transducers to measure QUS parameters: normalized BUA (nBUA), SOS and broadband ultrasonic backscatter (BUB). BMD was determined using QCT. Six hundred sixty non-overlapping ROIs were selected for quantitative analysis on both QUS and QCT images. Finally, 37 cylindrical cores were extracted from 31 specimens (8 mm diameter). Their micro-architecture was derived using micro-tomography. All QUS parameters were significantly correlated to BMD (nBUA: r^2=0.7; SOS: r^2=0.75; BUB: r^2=0.44). Multiple regression models were tested with BMD and micro-architecture. SOS only was best explained by a combination of bone quantity (BV/TV) and micro-architecture parameters (SOS with BMD and structure model index: r^2=0.93). No additional variability of nBUA and BUB could be explained by micro-architectural parameters in addition to BMD or BV/TV. These results suggest that QUS measurement at the hip may be relevant for fracture risk prediction.

11:00 am: 1aBB10

Author(s): Emmanuel Bossy[1], Frederic Padilla[2], Frederic Jenson[2], Guillaume Haiat[2], Pascal Laugier[2]

Affiliation: [1]Dept. of Aerosp. and Mech. Eng., Boston Univ., Boston, MA 02215;

[2]Laboratoire d'Imagerie Paramtrique, 75006 Paris, France

Title: Numerical simulation of wave propagation in cancellous bone

Abstract: Physical mechanisms implied in the propagation of ultrasound waves in trabecular bones are not yet clearly understood. The relative role of scattering and absorption in the attenuation process is unknown. To dissociate these two effects, a simulation of wave propagation in 3D volumes of trabecular bone is performed, and compared to experimental results. The simulation algorithm accounts for scattering and volumetric absorption into both the saturating fluid and bone. The simulation software uses a finite difference approach based on the Virieux numerical scheme. An incident plane wave is propagated on a volume of bone of approximately 5x5x8 mm[sup 3]. These volumes were reconstructed from high resolution micro-CT experiments. Several types of simulations are computed: bone described as a fluid matrix saturated by fluid (i.e., neglecting the shear wave propagation into the matrix) and bone described as a solid matrix saturated by fluid, with or without absorption. From the transmitted signals, attenuation and speed of sound through the specimens are calculated and compared to experimental values obtained on the same specimens. Finally, the contribution of scattering to the total attenuation is estimated, and the importance of mode conversions as well as absorption.

11:15 am: 1aBB11

Author(s): Simon P. Dodd[1], James L. Cunningham[1], Anthony W. Miles[1], Victor F. Humphrey[2], Sabina Gheduzzi[3]

Affiliation: [1]Ctr. for Orthopaedic Biomechanics, Univ. of Bath, Bath, BA2 7AY, UK; [2]Univ. of Southampton, Southampton, SO17 1BJ, UK; [3]Univ. of Bristol, Bristol, BS10 5NB, UK

Title: Ultrasonic wave propagation in cortical bone mimics

Abstract: Understanding the velocity and attenuation of ultrasonic waves in cortical bone is important for studies of osteoporosis and fractures. In particular, propagation in free- and water-loaded acrylic plates, with a thickness range of around 1--6 mm, has been widely used to mimic cortical bone behavior. A theoretical investigation of Lamb mode propagation at 200 kHz in free- and water-loaded acrylic plates revealed a marked difference in the form of their velocity and attenuation dispersion curves as a function of frequency thickness product. In experimental studies, this difference between free and loaded plates is not seen. Over short measurement distances, the results for both free and loaded plates are consistent with previous modeling and experimental studies: for thicker plates (above 3--4 mm), the velocity calculated using the first arrival signal is a lateral wave comparable with the longitudinal velocity. As the plate thickness decreases, the velocity approaches the S[inf 0] Lamb mode value. <scap>Wave2000 modeling of the experimental setup agrees with experimental data. The data are also used to test a hypothesis that for thin plates the velocity approaches the corresponding S[inf 0] Lamb mode velocity at large measurement distances or when different arrival time criteria are used. [Work supported by Action Medical Research.]

11:30 am: 1pBB12

Author(s): Kay Raum[1], Ingrid Leguerney[2], Florent Chandelier[2], Maryline Talmant[2], Amena Saied[2] , Pascal Laugier[2], Francoise Peyrin[3]

Location:

Affiliation: [1]Q-BAM Group, Dept. of Orthopedics, Martin Luther Univ., 06097 Halle, Germany; [2]Laboratoire d'Imagerie Paramtrique, 75006 Paris, France; [3]CREATIS and European Synchrotron Radiation Facility, 38043 Grenoble, France

Title: Structural and elastic determinants of axial transmission ultrasonic velocity in the human radius

Abstract: Accurate clinical interpretation of the sound velocity derived from axial transmission devices requires a detailed understanding of the propa-gation phenomena involved and of the bone factors that have an impact on measurements. In the low-megahertz range, ultrasonic propagation in cortical bone depends on anisotropic elastic tissue properties, porosity, and the spatial dimensions, e.g., cortical thickness. A subset of ten human radius samples from a previous biaxial transmission investigation was inspected using 50-MHz scanning acoustic microscopy (SAM) and synchrotron radiation computed tomography (SR-CT). Low-frequency axial transmission sound speed at 1 and 2 MHz was related to structural properties (cortical thickness C.Th, porosity POR, Haversian cavity density CDH) and tissue parameters (acoustic impedance Z, mineral density MD) on site-matched cross sections. Significant linear multivariate regression models (1 MHz: R=0.84, p<1E-4, 2 MHz: R=0.65, p<1E-4) were found for the combination of C.Th with POR and Z (measured in the external cortical quarter). A modified model accounting for the nonlinear dispersion relation with C.Th was also highly significant (R=0.75, p<1E-4, rmse=49.22 m/s) and explained (after adjustment for dispersion) 55.6% of the variance of the sound velocity by variations of porosity (15.6%) and impedance (40%).

11:45 am: 1aBB13

Author(s): M. Talmant, E. Bossy, P. Laugier

Affiliation: Laboratoire d'Imagerie Parametrique, UMR CNRS 7623, 15 rue de l'ecole de Medecine, 75006 Paris, France

Title: Simulated axial transmission propagation on cortical bone

Abstract: The ultrasonic axial transmission technique, used to assess cortical shells of long bones, is investigated using numerical simulations. The 3-D finite difference code generates synthetic signals recorded at different distance emitter--receiver for a linear arrangement of transducers placed along the bone axis. Academic modeling of bone based on cylindrical tubular shape made of anisotropic and porous material has been reported [J. Acoust. Soc. Am. 115 (2004)]. The aim of this paper is to refine the model by taking into account more realistic structural and material bone properties. Finite difference modeling was applied to 50 human radius specimens which were examined both by x-ray tomography at different resolutions and by ultrasonic axial transmission technique (1 MHz). The x-ray macroscopic geometry (pixel around 100 (mu)m) of the 50 samples was imported in the code. Material properties are assigned to each bone according to its own microarchitecture examined at a 10 (mu)m scale. Different assumptions of the relationship between bone structural properties and material properties were tested. Simulations were

validated by comparison with experimental results. Numerical simulations of transient propagation in bone is a powerful tool to enlighten interaction between ultrasound and bone and consequently to improve ultrasound based devices for clinical use.

12:00 pm: Lunch

Topical Meeting on Ultrasound Characterization of Cancellous and Cortical Bone II: Experimental Techniques
and
Clinical Impact and Comparison with Other Modalities

1:00 pm: 1pBB1 **(INVITED)**

Author(s): Pascal Laugier

Affiliation: Universite Pierre et Marie Curie CNRS 7623, Paris, France

Title: The use of ultrasound to probe structural and material properties of bone: Sate-of-the-art

Abstract: The knowledge of the elastic properties of bone can be used to investigate the effects of aging, disease, and treatments. Elastic properties are also required as input for both computational and analytic models. An alternative approach to direct bone mechanical testing is to use ultrasonic testing. Furthermore, ultrasound is appropriate for multiscale analysis. In vitro, ultrasound has been widely used to derive nondestructively the stiffness coefficients or the elastic moduli at the whole specimen level at low frequency (structural elasticity) or at the tissue level at higher frequency (material stiffness). Quantitative ultrasound (QUS) techniques have also been developed for in vivo skeletal status assessment based on the assumption that ultrasonic properties reflect skeletal factors of bone fragility. In vivo QUS is then used to predict fracture risk. Several different techniques are currently available or under development involving different type of waves (bulk compressional waves, surface waves, guided modes). Measured ultrasonic properties in transmission or in reflection depend on a variety of material properties and macro- or micro structural characteristics. However, the complexity of the interaction mechanisms between the incident ultrasonic field and bone is still not fully elucidated and requires a better understanding.

1:25 pm: 1pBB2 **(INVITED)**

Author(s): Armen Sarvazyan, Alexej Tatarinov

Affiliation: Artann Labs., 1753 Linvale-Harbourton Rd., Lambertville, NJ 08530

Title: Use of guided ultrasonic waves for characterization of cancellous and cortical bone

Abstract: The possibility of accessing mechanical, structural, and geometrical parameters of both the cancellous and cortical bone components by different modes of ultrasonic guided waves has been demonstrated in several laboratories in Europe and the USA. Making measurements of acoustic wave propagation parameters in a wide frequency band, e.g., from 100 kHz to several MHz, enables assessment of bone layers at different depths from the bone surface. At lower frequencies, the acoustic wave velocity is found to be sensitive to changes of the cortical thickness in middleshaft areas. In epiphyseal zones, the measured low-frequency (100-kHz) wave, velocity reflects contributions of both the spongy and compact bone components and can be sensitive to changes of the trabecular structure. At higher frequencies in the MHz range, the main acoustic mode manifested in the received signal is related to the longitudinal wave, which characterizes mainly the elastic properties of the compact bone closer to the periosteum. Measurements of the

ultrasonic pulse propagation parameters in a broad frequency band using surface transmission scanning mode enables the possibility to obtain the profile of acoustic properties of long bones. [Work supported by NIH and NASA.]

1:50 pm: 1pBB3 **(INVITED)**

Author(s): Kay Raum

Affiliation: Location: Q-BAM Group, Dept. of Orthopedics, Martin Luther Univ., 06097 Halle, Germany; Laboratoire d'Imagerie Paramtrique, UMR CNRS 7623, France

Title: Scanning acoustic microscopy on bone - Status and perspectives

Abstract: High-frequency ultrasound has become one of the most powerful tools for the elastic characterization of hard materials since its invention in 1974. Many of the imaging and measurement techniques developed for NDE were also applied for the characterization of bone. However, the heterogeneous structure at several levels of organization implies multifold problems, e.g., tissue preparation, validity and applicability of the measurement techniques, resolution limitations, interpretation of results, etc. Furthermore, the technical development of commercially available high-resolution SAM lacks far behind other quantitative imaging modalities. The talk will describe the acoustic microscopes developed in our group, concepts for acoustic impedance mapping with frequencies up to 1 GHz, and techniques for determining longitudinal, shear, and surface wave velocities. The relations of acoustic to elastic parameters, either directly derived from the acoustic measurement or obtained from micromechanical tests, are presented. Combinations with other experimental and clinical techniques (US, SR-CT, nanoindentation, Raman) demonstrate the potential of SAM for an improved diagnosis, both in experimental and in clinical studies. In vitro results demonstrate the feasibility for assessing the elastic anisotropy and microstructural parameters of cortical bone, compositional variations within alternating osteon lamellae, structural and elastic changes in arthrotic cartilage and subchondral bone, respectively.

2:15 pm: 1pBB4

Author(s): Frederic Jenson, Frederic Padilla, Pascal Laugier

Affiliation: Laboratoire d'Imagerie Paramtrique, CNRS UMR 7623 Universit Paris 6, 15 rue de l'Ecole de Medecine, 75006 Paris, France

Title: Influence of the precision of spectral backscatter measurements on the estimation of scatterers size in cancellous bone

Abstract: Ultrasonic backscatter measurements can be used to characterize trabecular bone structure and to estimate trabecular thickness (Tb.Th, i.e., the size of the scatterers). Our objective was to evaluate the performance of this estimator as well as others spectral estimators, like the frequency dependence and the mid-band amplitude of the backscatter coefficient. The performance of these estimators is degraded mainly by two factors: interference noise due to random positioning of the scatterers and attenuation. We have simulated rf-lines backscattered from trabecular bone assuming a random positioning of the trabeculae (leading to a fully developed speckle), a Gaussian form factor for the scatterers and a linear-frequency dependent attenuation. It is found that the variance in the estimation of the frequency dependence of the backscatter coefficient is as high as the variance due the biological variability in Tb.Th, in agreement with the results showed by K. Wear [J. Acoust. Soc. Am. SA, 110 (2001)]. In contrast, the variances on the mid-band amplitude and on the estimated trabecular thickness are lower than the variance due the biological variability. We also show that the effect of attenuation may be compensated by using an appropriate attenuation-compensation function. These results suggest that the inverse problem can be appropriately addressed.

2:30 pm: 1pBB5

Author(s): Kay Raum[1], Florent Chandelier[2], Ingrid Leguerney[2], Maryline Talmant[2], Amena Saied[2], Pascal Laugier[2], Francoise Peyrin[3]

Affiliation: [1]Q-BAM Group, Dept. of Orthopedics, Martin Luther Univ., 06097 Halle, Germany; [2]Laboratoire d'Imagerie Paramtrique, 75006 Paris, France; [3]CREATIS and European Synchrotron Radiation Facility, 38043 Grenoble, France

Title: Assessment of cortical bone microstructure and material properties using high resolution scanning acoustic microscopy

Abstract: Combined evaluation of bone microstructural and mechanical information remains a challenging task which is required for bone phenotyping or accurate finite element modeling. Our objective was to assess the value of quantitative scanning acoustic microscopy (SAM) for bone characterization in comparison to synchrotron radiation computed tomography (SR-CT). Ten specimens of human cortical bone (radius) were investigated using SR-CT and SAM (200 MHz) with spatial resolution of 10 and 8 µm, respectively. An image fusion and analysis software was developed to derive site-matched estimates of (1) microstructural parameters, e.g., haversian cavity density and mean diameter and porosity, and (2) tissue properties such as mineral density (MD, SR-CT) and acoustic impedance (Z, SAM) for distinct anatomical regions of interest (osteons, interstitial tissue). Local stiffness c_{33} was derived from the combination of MD and Z. An almost perfect correlation was found for all microstructural indices derived by both techniques. Impedance was correlated to the square of MD (R^2=0.39, p<1e-4). The derived stiffness c_{33} (35.9 ± 12.8) was highly correlated with Z (R^2=0.99, p<1e-4). These findings suggest that SAM fulfills the requirement for a simultaneous evaluation of cortical bone microstructure and material properties at the tissue level.

2:45 pm: 1pBB6

Author(s): E. Bossy[1], M. Talmant[1], P. Laugier[1], C. Roux[2], S. Kolta[2], D. Haguenauer[3]

Affiliation: [1]Laboratoire d'Imagerie Parametrique, UMR 7623, 15 rue de l'ecole de Medecine, 75006 Paris, France; [2]CEMO, 75014 Paris, France; [3]Hopital Ste Perrine, 75016 Paris, France

Title: Correction for soft tissue in cortical bone assessment by ultrasound

Abstract: One of the key points in ultrasound measurements on cortical bone is the correction for soft tissue. We designed a new probe based on bi-directional axial transmission which automatically compensates velocity measurements for the soft tissue effect without preliminary evaluation of soft tissue properties. The probe consists in a

linear arrangement of transducers with two sources placed on both sides of a unique group of receivers. The velocity of waves propagating parallel to the bone axis is deduced from a combination of the time delays derived from waves propagating in opposite directions at successive receivers separated by a known distance. This technique efficiently corrects for the major source of error on velocity encountered in clinical measurements which is caused by the variation of soft tissue thickness along the probe. The bi-directional technique was validated on test samples for which the residual precision error on velocity measurements was reduced to 0.2%. In vivo measurements yielded a value of 0.5% for the interoperator reproducibility. The clinical range of variation of the velocity measured by bi-directional technique is evaluated using clinical measurements on more than 200 subjects. Bi-directional transmission is a promising technique to minimize the variability of in vivo velocity measurements.

3:00 pm: Break

3:15 pm: 1pBB7 **(INVITED)**

Author(s): Peter P. Antich[1], Matthew A. Lewis[1], Edmond Richer[1], Billy J. Smith[1], Charles Y. C. Pak[2]

Affiliation: [1]Adv. Radiological Sci., Univ. of Texas Southwestern Med. Ctr., Dallas, TX 75390-9058; [2]Univ. of Texas Southwestern Med. Ctr., Dallas, TX 75390

Title: Ultrasound critical angle-reflectometry: Measuring ultrasound velocities in the clinic and in the laboratory

Abstract: Ultrasound critical angle-reflectometry is a modality developed and tested for measuring US velocity in the laboratory or the clinic. The applicator developed for use in the clinic consists of a transmitter concentric to a receiver, immersed in water and capable of analyzing multiple reflections from soft and mineralized tissues over angles from -45º to 45º. If a critical angle ϑ_c is detected in the spectrum, the velocity in bone is simply $V=c/\sin\vartheta_c$. The analysis can be repeated at different orientations; considering only p-wave velocities, as bone has transverse symmetry, there is a unique relationship between velocity and coefficients of stiffness: $\rho V^2\varphi = C_{11}\cos^4\varphi + C_{33}\sin^4\varphi + 2\cos^2\varphi \sin^2\varphi(C_{13}+2C_{44})$. It can be shown that C_{11} and C_{33} give two orthogonal moduli of elasticity. Experiments show that the modulus of elasticity so derived is equal to that measured by mechanical testing. In addition to these angles we can measure the arrival time of the reflected signal and identify the depth from which the signal originates; for cortical layers of sufficiently small thickness it is possible to identify cancellous bone critical angles. Examples are provided which show that these quantities vary in response to metabolic and physical stimuli.

3:40 pm: 1pBB8 **(INVITED)**

Author(s): Yixian Qin[1], Yi Xia[2], Wei Lin[2], Clinton Rubin[2], Barry Gruber[2]

Affiliation: [1]Dept. of Biomed. Eng., SUNY Stony Brook, 350 Psych-A Bldg., Stony

Brook, NY 11794; [2]SUNY Stony Brook, Stony Brook, NY 11794

Title: Assessment of trabecular bone quality in human cadaver calcaneus using scanning confocal ultrasound and DEXA measurements

Abstract: Microgravity and aging induced bone loss is a critical skeleton complication, occurring particularly in the weight-supporting skeleton, which leads to osteoporosis and fracture. Advents in quantitative ultrasound (QUS) provide a unique method for evaluating bone strength and density. Using a newly developed scanning confocal acoustic diagnostic (SCAD) system, QUS assessment for bone quality in the real body region was evaluated. A total of 19 human cadaver calcanei, age 66 to 97 years old, were tested by both SCAD and nonscan mode. The scanning region covered an approximate 40x40 mm[sup 2] with 0.5 mm resolution. Broadband ultrasound attenuation (BUA, dB/MHz), energy attenuation (ATT, dB), and ultrasound velocity (UV, m/s) were measured. The QUS properties were then correlated to the bone mineral density (BMD) measured by DEXA. Correlations between BMD and QUS parameters were significantly improved by using SCAD as compared to nonscan mode, yielding correlations between BMD and SCAD QUS parameters as R=0.82 (BUA), and R=0.86 (est. BMD). It is suggested that SCAD is feasible for in vivo bone quality mapping. It can be potentially used for monitoring instant changes of bone strength and density. [Work supported by the National Space Biomedical Research Institute (TD00207), and New York Center for Biotechnology.]

4:05 pm: 1pBB9 **(INVITED)**

Author(s): Patrick H. Nicholson

Affiliation: Dept. of Health Sci., Univ. of Jyvaskyla, P.O. Box 35, 40014, Finland

Title: Ultrasonic assessment of hone, comparison with other characterization modalities

Abstract: Compared to other techniques, quantitative ultrasound of bone (QUS) has a unique potential arising from the mechanical nature of the wave phenomena involved, the ability to use wavelengths spanning the dimensions of key structural features of bone, and the absence of ionizing radiation. However, QUS suffers from fundamental problems of interpretation when compared to most other bone assessment modalities. For example, dual energy x-ray absorptiometry gives a direct estimate of a well-understood physical parameter: bone mineral density. In contrast, QUS yields acoustic properties that cannot be so easily interpreted, and whose clinical value is derived largely from empirical relationships with physical properties of interest, such as bone density, or with other factors such as risk of fracture. Hence for QUS we cannot trace a clear causal path connecting an ultrasonic measurement to specific bone properties and on, in turn, to clinical outcomes and decisions. Without developing the theoretical framework required to achieve this, QUS will not achieve its full potential and is likely to remain sidelined and mistrusted in comparison to the x-ray-based modalities which are its principal competitors.

4:30 pm: 1pBB10

Author(s): M. Muller1, M. Talmant1, P. Laugier1, P. Moilanen2, V. Kilappa2, J. Timonen2, P. Nicholson2, S. Cheng2

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Title: In vitro comparative study of three devices based on ultrasonic axial transmission

Abstract: In the axial transmission technique the velocity of waves propagating in the direction of bone axis is used to characterize cortical bone (radius, tibia, etc.). Corresponding clinically used devices are based on a long wavelength approach (typical frequency around 200 kHz) or shorter wavelength (typical frequency around 1 MHz) compared to bone thickness. They differ also by the methods of wave velocity evaluation. The aim of this study is to compare the sensitivity to bone properties of three representative devices using an in vitro investigation of the same specimens coupled with x-ray determination of bone properties. The moderate correlation between velocities suggests an important impact of site-matching. Among higher frequency devices, the one associated to the bidirectional probe provided generally higher correlation with bone properties than conventional axial transmission. The high-frequency devices are less sensitive to cortical thickness, CSA and trabecular BMD than the low-frequency device because high-frequency waves interrogate a thinner cortical layer than low-frequency waves. Our results suggest that different axial transmission approaches reflect different bone properties. Therefore, a multi-frequency technique might be useful in probing different bone properties at the same time (e.g., cortical thickness and BMD).

4:45 pm: 1pBB11

Author(s): Jonathan J. Kaufman[1], Gangming Luo[1], Miriam Englander[2], Robert S. Siffert[2]

Location: Mount Sinai School of Medicine, New York, NY 10029

Affiliation: [1]CyberLogic, Inc., 611 Broadway, Ste. 707, New York, NY 10012; [2]Mount Sinai School of Medicine, New York, NY 10029

Title: A new system for clinical ultrasound assessment of bone

Abstract: A new ultrasound device for noninvasive assessment of bone known as the QRT 2000 for Quantitative Real-Time---that is entirely self-contained, portable, and handheld is described. The QRT 2000 is powered by 4 AA rechargeable batteries and permits near real-time evaluation of a novel set of ultrasound parameters and their on-line display to the user. A clinical study has just been completed with the QRT 2000 in which 60 female subjects ranging in age from 25 to 88 were ultrasonically interrogated at their heels. The same heel was measured also using DEXA (PIXI, GE Medical Systems) and the bone mineral content (BMC) was compared with one ultrasound parameter which has been found to be extremely sensitive to bone mass. The parameter, known as the net time delay (NTD), and BMC had an associated R-squared value of 0.73, about a 13% improvement over presently marketed devices. This, coupled with the lower cost and portability of the system, makes the QRT 2000 ideally suited for use by primary care physicians in this country and abroad, and including for use in the developing world. Further improvements are being pursued through array methods (to improve reproducibility and correlations with BMD) and by incorporating other parameters particularly sensitive to architectural structure. [This research was supported by SBIR Grant No. 2R44AR045150 from the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the NIH.]

Panel Discussion

5:00 pm

Panelists: Peter Antich, Pascal Laugier, Armen Sarvazyan, and Keith Wear.

Format: The Panel Discussion will last one hour. We plan to cover a range of topics, from models to laboratory measurements to clinical use. Each panelist will be offered approximately 5 minutes to describe his interest and involvement in the research of ultrasound characterization of bone as well as describe a current problem(s) that impedes the progress of the research. After each panelist has spoken, panelists will be offered the opportunity to ask each other questions. Questions from the audience will then follow.

6:00 pm: Adjourn